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Efficiency improvement and potential LCOE reduction with an LFR-XX SMS plant with storage

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Abstract

Several forms of renewable energy have in the last decade achieved a remarkable technological improvement and cost effectiveness, including Solar Energy. Photovoltaic systems (PV) are reaching grid parity in the sunniest regions of Europe. Apart from PV, a promising technology is Concentrated Solar Power (CSP) with thermal storage, because it enables higher power plant availability throughout the year as well as dispatchability, a highly important and valuable feature for a power plant. However significant cost reductions are still to be achieved, for CSP to be competitive with conventional electricity production and with PV.

In this paper a few technological improvements are described and a proposal is made to combine them in a system that is more efficient and has, simultaneously, the potential of being cheaper. The goal is to show the potential for advanced LFR concepts in combination with high temperature molten salt mixtures and energy storage as being also important contenders to the objective of bringing STE- Solar Thermal Electricity to the market in a competitive way. The concept presented and developed includes a higher ΔT of the heat transfer fluid (HTF), a particular storage strategy and a new optical concept based on a new Linear Fresnel Concentrator (LFR XX SMS-Simultaneous Multiple Surface, Fig.1,2, [1] enabling an important increase in the overall yearly solar to electricity conversion efficiency and generating an important potential for electricity cost reduction. It is shown that values approaching 10eurocents/kWh, for a 50MW plant with 7 hours storage capacity are possible in Southern Europe.

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Keywords: CSP; Fresnel; storage; molten salts; LCOE

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Nomenclature

E_{TES}	Total Thermal Energy Storage Capacity [Wh]
$\eta_{Cycle,OUT}$	Cycle efficiency at design conditions [-]
P_{OUT}	Power output [W]
Δt_{TES}	Thermal Storage Capacity [h]
$\rho_{TES,\max};\rho_{TES,\min}$	Specific Volume of the TES medium [g/m^3]
$c_{TES,\max};c_{TES,\min}$	Heat capacity of the TES medium [W/g* m^3]
HTF	Heat Transfer Fluid
$T_{SF,return}$	Return Temperature of the Solar Field medium [ºC]
$T_{SF,in}$	Inlet Temperature of the Solar Field medium [ºC]
f_{HE}	Heat Exchanger Efficiency Factor, Solar Loop / Storage Loop [-]
DNI	Direct Normal Irradiation [kWh/m^2]
I_t ; M_t ; F_t ; E_t	Investment, Operation and Maintenance, Fuel costs, Electricity generation of period “t”
r	Interest Rate

1. Introduction

Low cost thermal electricity can be achieved by raising the efficiency of the solar plant and/or lowering the cost of its components, installation costs, operating strategy, etc. This paper is about presenting a solution to tackle both ways at the same time.

On the efficiency side the paper proposes the use of a new Linear Fresnel concentrating optics with a much higher performance than that usually associated with conventional LFR, permitting operation at much higher temperatures (for higher thermodynamic conversion efficiency) in association with molten salt as HTF fluid. On the cost side, the use of LFR is, in general, associated with lower field costs and simplified operation (fixed receiver, ease of mirror cleaning, substantially less piping, etc).

The paper aims at showing the potential of combining highly perfuming linear optics with new tendencies in terms of operating temperatures, further exploring the potential and advantages of linear optics as an alternative to CR- Central Receiver solutions already commercially used for these temperatures and HTF.

With the improved LFR concept used in this paper, in combination with molten salt as HTF, it will be argued that it is possible to propose a solar plant capable of producing dispatchable electricity at a cost approaching or even falling below 10 eurocents/kWh.

1.1 New Linear Fresnel optics: the potential for Optical Efficiency Improvement

The field of Non Imaging Optics although it has been developed since the late 70’s as a separate research field related to Solar Energy, still has a lot of potential for further improvement in solar related topics. One of the most promising areas is within Solar Fresnel Concentrating technologies, since conventional LFR is still far from the theoretical limits that can be achieved for the concentration factor. Developments from the conventional LFR include the Compact Linear Fresnel Reflector (CLFR) [3], the Etendue Matched upgrade (CLFR-EM) [4], and recently the LFR XX SMS-Simultaneously Multiple Surface-Concept [1], an application derived from the SMS concept [13,14].

The new XX-SMS is fully characterized in a paper just accepted for publication in Solar Energy, where it is compared to others (one LFR with a CPC type second stage concentrator and a PT). Thus, and for the sake of space, it is not described in this paper in more detail and compared to others.

The XX SMS LFR is a solution quite different from all others presented up to now. It achieves [1] a very high concentration (C=74) and an unprecedently high CAP-Coefficient of Angular Performance (0.57) for a full acceptance angle of 0.88deg, just like the acceptance angle of the concentrator commercially proposed in [11]. Designing for the same acceptance angle is in line with the idea of presenting a new concept not requiring tracking accuracy and manufacture tolerances different from what can be found already on the market.

This new concept aims at having a primary reflector field where shading and blocking are controlled, and the concentration factor is increased in order to achieve a higher final conversion efficiency, resulting from lower thermal losses.

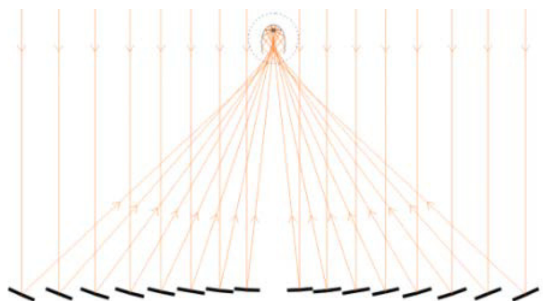

Fig. 1 LFR XX SMS Concept

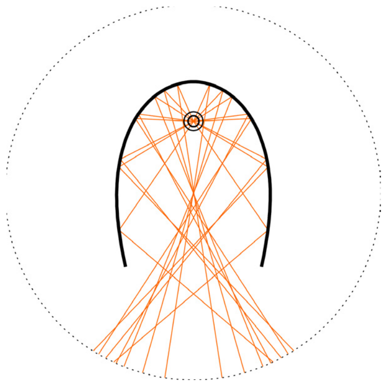

Fig. 2. LFR XX SMS Concept, detail of the secondary

Fig. 1 shows a cross-section of the new concept with a detail of the second stage concentrator (Fig.2), displaying its SMS continuous curve, with no cusp as required in the CPC type secondary on the market [11], thus with a potential for easier fabrication.

Table 1 shows the main optical characteristics of the new concentrator described in [1] and designed for an evacuated tube with 70mm receiver diameter, for which the main material properties considered were the ones in Table 2.

Table 1- Details of the new XX-SMS concentrator

Concept	Primary width (m)	Total mirror aperture length (m)	Receiver Height (m)	Number of mirrors	Mirror length (m)	φ (°)	C (X)	θ (°)	CAP_0	η_{opt0}	η_{opt0}^{*}
InnovLFR	20.11	17.1	9.8	16	1.06[1]	45.79	73.71	0.44	0.57	0.69	0.72

Table 2- Materials properties used in the calculations of Table 1

	Reflectivity	Absorptivity	Transmissivity
Primary Mirror	92% ([11])	-	-
Secondary Mirror	92% ([11])	-	-
Receiver Tube	-	95% ([7])	-
Glass Cover	-	-	96% AR-coated glass tube ([7])

To fully characterize [1] the optical performance of the concentrator, its IAM – Incidence Angle Modifier-behavior was considered through a ray tracing matrix of longitudinal and transversal angular pairs.

These performance characteristics were than used in Section 2 in a simulation tool considering hourly DNI – Direct Nominal Irradiance data used as input for the yearly energy simulation, which considers a Fresnel Plant of 50MWe in Faro (Portugal) and Hurghada (Egypt).

[1] This is the mean value, i.e., not all the heliostats have the same width due to the optimization process.

1.2. Molten salt and high temperature operation

There are several heat transfer media being used in solar systems. Up to 400ºC the most common is the usage of mineral oils and synthetic fluids, however they are expensive and have a rather low temperature upper limit, for that reason molten salts are more and more used as an alternative, since it enables an increase in the conversion efficiency. Extensive research concerning the development of new mixtures is ongoing [5].

Molten salts can be of two origins: extracted as a raw material from nature with a variable degree of impurities and as a result of industrial processes, which normally guarantees a lower level of impurities and better characterization. To choose a solar salt, apart from the cost, the following aspects are important: operative temperature range, thermal stability at high temperature, corrosion issues. For storage, currently almost all commercial plants use the traditional solar salt (60% $NaNO_3$, 40% KNO_3), however there has been wide research to find alternatives, for cost reasons, or for lowering/increasing the operative temperatures.

The idea of using molten salt as the proposed HTF provides as well the capacity for energy storage through its direct storage in suitable tanks. For CSP plants with storage the most common storage configuration is the 2-tank indirect system which is connected to the solar field loop through a heat exchanger. This layout using thermal oil up to 400ºC in the solar side and molten salts on the storage loop became the standard not because it is an optimized solution, but for a risk aversion issue when planning recently built plants like Andasol in Spain, since there was knowhow on these type of systems in California, USA in the 80´s. For that reason and due to legislative 50MWe limitation in Spain, the design of most plants is very similar, as in the case of Andasol-1/2/3, as well as Termesol-1/2, Valle-1/2, Extresol-1/2/3 in Spain, Solana in the USA [2].

In Italy, the Priolo Gargalo 5 MWe plant is in operation since 2010, has a direct molten salt parabolic through system, using two tanks with a maximum temperature of 550ºC. In Spain, a different concept, Gemasolar with a direct molten salt tower system, up to a temperature of 565ºC, in operation since 2011. Both plants show the possibility to successfully operate a plant with molten salt as the HTF at a considerable higher temperature than the standard 400ºC with thermal oil, which enables a higher conversion efficiency of the power block, increasing from 36-37% to 41-42% according to state-of-the-art turbines. In the calculations made solar salt is considered both as transfer as well as storage medium.

1.3. Linear Fresnel System using molten salts

With the development of ternary and quaternary mixtures, in the future it is foreseen that molten salts will be more and more used as heat transfer fluid (HTF) also in the solar loop, both for Parabolic through collectors (PTC) and specially Linear Fresnel, since molten salts as a transfer media have a very interesting fit with Linear Fresnel technology as presented in the following table.

Table 3. Comparison of Fresnel and Parabolic Through Collectors for usage with molten salts

Sub-systems	Fresnel – LFR	Parabolic – PTC
Heat Transfer	Usage of a secondary concentrator	Less impact if using a secondary concentrator
Concentration Ratio	Can be significantly increased by means of an optimized design primary + secondary (for instance the new LFR XX SMS)	Small efficiency increase possibility due to a higher impact of the shading effect of a possible second stage concentrator
Draining	Easy to drain since receivers are at about 10m high	Difficult to drain since receivers are at a lower position and there are flexible movable parts
Joints	Receivers are fixed with no moving parts, easier Operations, less Maintenance costs	Receivers move according to solar tracking, higher Operation and Maintenance costs
Solar Tracking	Possibility to focus or defocus in small steps (move just a few primary mirrors) which enables a better control of the energy output and molten salt temperature	Only 3 modes possible: 1- full sun tracking; 2- partial following; 3- out of sun
Hydraulic Circuit	Less receivers (higher concentration) and less piping (more compact) leading to lower losses	Higher pressure drop due to longer and more complex piping system

2. Yearly energy simulation : new LFR XX SMS concept

2.1. Introduction

This paper makes no attempt at optimizing a particular plant configuration, as for instance in terms of storage size, solar multiple, etc., since the new SMS optics has not been demonstrated yet and given all the uncertainties concerning things like mirror costs, molten salt operation in LFR systems, etc, it would be superfluous to attempt such an optimization. This paper simply considers a new combination of components for a possible 50MW plant designed to provide dispatchable electricity (through the consideration of 7 hours of storage- a common choice) and calculates its performance in order to show that an LCOE value on the order of 10 euro cents/kWh is well within reach.

As for the molten salt operating experience and related figures used in the calculation the reference is the GEMASOLAR/TORRESOL tower plant already operating with molten salts at 565ºC and producing steam at 545ºC (100bar). The experience about operating molten salts at high temperature in linear focus systems comes also from ENEA [12], but no experience really exists on a demonstration/plant scale with Molten salts combined with LFR technology.

2.2. Simulation with no storage

A calculation was first made for solar to electricity efficiency of a 50MW plant using the assumptions presented in Table 4.

Table 4. Assumptions for the yearly calculation, case: no storage

Optics	LFR XX SMS as defined in [1]
Location	Faro-PT (37º01'N, 2234kWh/m2); Hurghada-EGY (27º26'N, 30434kWh/m2), Meteonorm data
Receivers	Evacuated tubular receiver, 70mm, considering 800W/m heat loss at 565ºC
HTF	60% Na NO3, 40% K NO3, heat exchange (98% efficiency) design point at 565ºC
Steam Cycle	Steam generation design point at 545ºC and 100 bar, turbine efficiency of 0,41
Solar Field	210.000 m2: 13 rows of 933m length
Piping	Connecting piping length: 2300m considering heat losses of 130W/m

Table 5. Expected performance in Faro and Hurghada

	Thermal energy delivered [kWh]	Electricity produced [kWh]	Total average yearly efficiency [-]
Faro	1.54×10^{8}	6.17×10^{7}	**0.138**
Hurghada	2.43×10^{8}	9.77×10^{7}	**0.160**

A detailed simulation, including hourly radiation and thermal losses, for operation at 565ºC was performed. Results are presented in Table 5, for the two locations.

This result is significantly higher than the one obtained with conventional LFR designs and plants, which would show, for the same location- Faro, a value on the order of 9% or below [9].

2.3. Simulation with storage

2.3.1 Thermal storage sizing

Using salt mixtures proposed in the literature [5], it is possible to have a higher operative molten salt temperature close to 600ºC as well as a higher ΔT, which is a key factor in order to have an increase of the energy output of the plant, enabling a cost reduction also from the fact that a higher ΔT enables a reduction on tank size, for the same storage capacity.

When designing a CSP plant, a key relevant figure is the total amount of energy that can locally be supplied to the grid, which is associated to a limit on the installed power. If there is a storage possibility, than the total plant energy output can considerably be increased, and a production shift can occur from the peak solar radiation hours into the night within the defined power capacity. This production shift, which can occur at any given time of the day, increases the dispatchability level of CSP plants, thus increasing its market value, a considerable advantage of Concentrated Solar Power when compared with PV.

For that reason, the optimum sizing of the storage capacity for a given location is a quite important figure. For a certain plant, the total Thermal Energy Storage (TES) thermal capacity is given by,

$$E_{TES} = \frac{P_{OUT}\Delta t_{TES}}{\eta_{Cycle,OUT}} \quad (1)$$

With the stored energy calculated, Eq.1, it is possible to compute the total Volume of Thermal Energy Storage necessary,

$$V_{TES} = \frac{E_{TES}}{\frac{\rho_{TES,\max} + \rho_{TES,\min}}{2} \times \frac{c_{TES,\max} + c_{TES,\min}}{2} \times \left(T_{SF,return} - T_{SF,in}\right) \times f_{HE}} \quad (2)$$

In case the solar loop and storage loop media are the same, for instance using molten salts as both media, than

$$f_{HE} = 1 \quad (3)$$

From an operational point of view, having 2 tanks, one "hot" (at the return temperature of the solar field) and one "cold" (at the inlet temperature of the solar field) has advantages, and thus, the total storage volume is usually divided into two tanks of equal size. Because of cost savings, a possible alternative could be the usage of just one tank thermally stratified, like thermocline storage.

2.3.2 Yearly energy with the New Fresnel Concept

Considering the new optics described, an yearly energy yield for a 50MWe Fresnel plant with storage has been simulated using TRNSYS. Storage size was chosen to be about 7 hours, a typical choice for most of the PT plants with storage operating in Spain. Besides the data used in Table 3, data input used also considers:

Table 6: Main Technical Data

Location	Faro – PT (38.57N, 7.91W, 2234 kWh/m2*year Meteonorm Data)
Total Primary Surface	Solar Multiple 2: 420 000m2
Optical Efficiency	0,69
Solar Resource design DNI for peak	950 W/m2
Turbine Full Load Efficiency	41%
Operating Temperature	290ºC to 565ºC
Storage	2 Tanks enabling 7h of TES (Direct system,1010MWhth)

In the following figures an idea of the system yearly performance as calculated with TNRSYS is shown: optical, storage and electricity output.

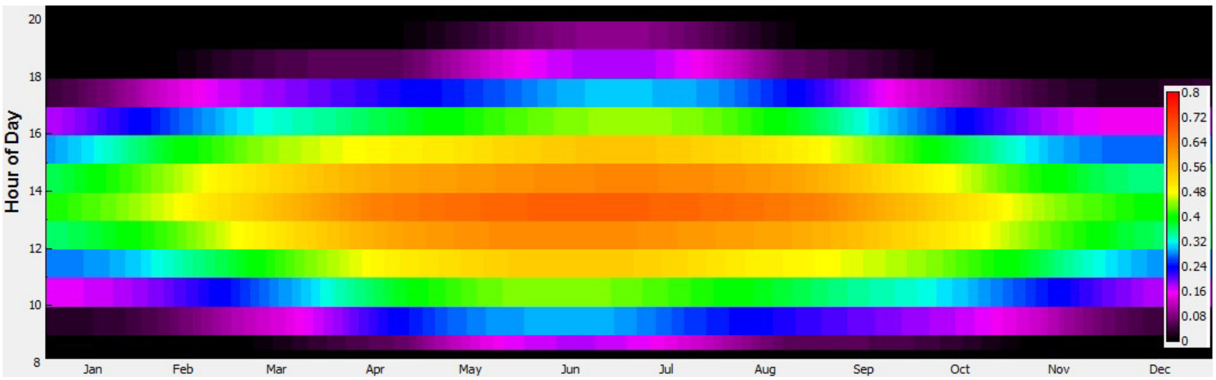

Fig.3 Yearly Optical Efficiency

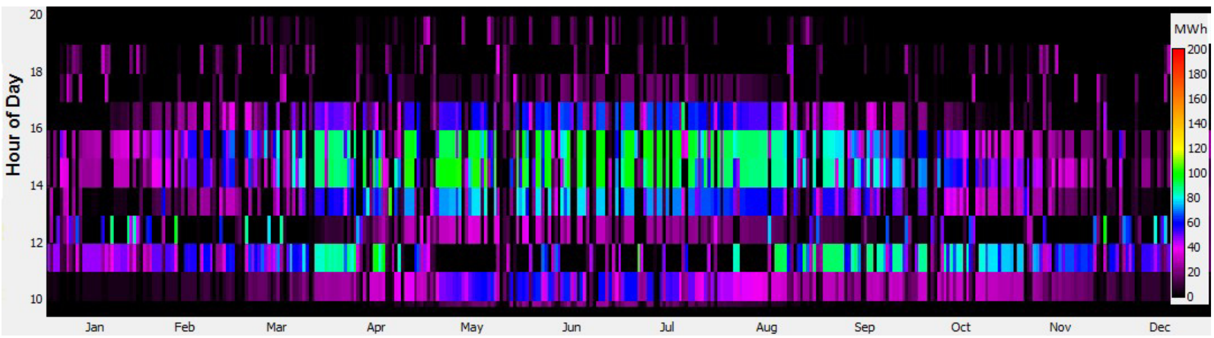

Fig.4 –Thermal energy sent to storage tank through the year

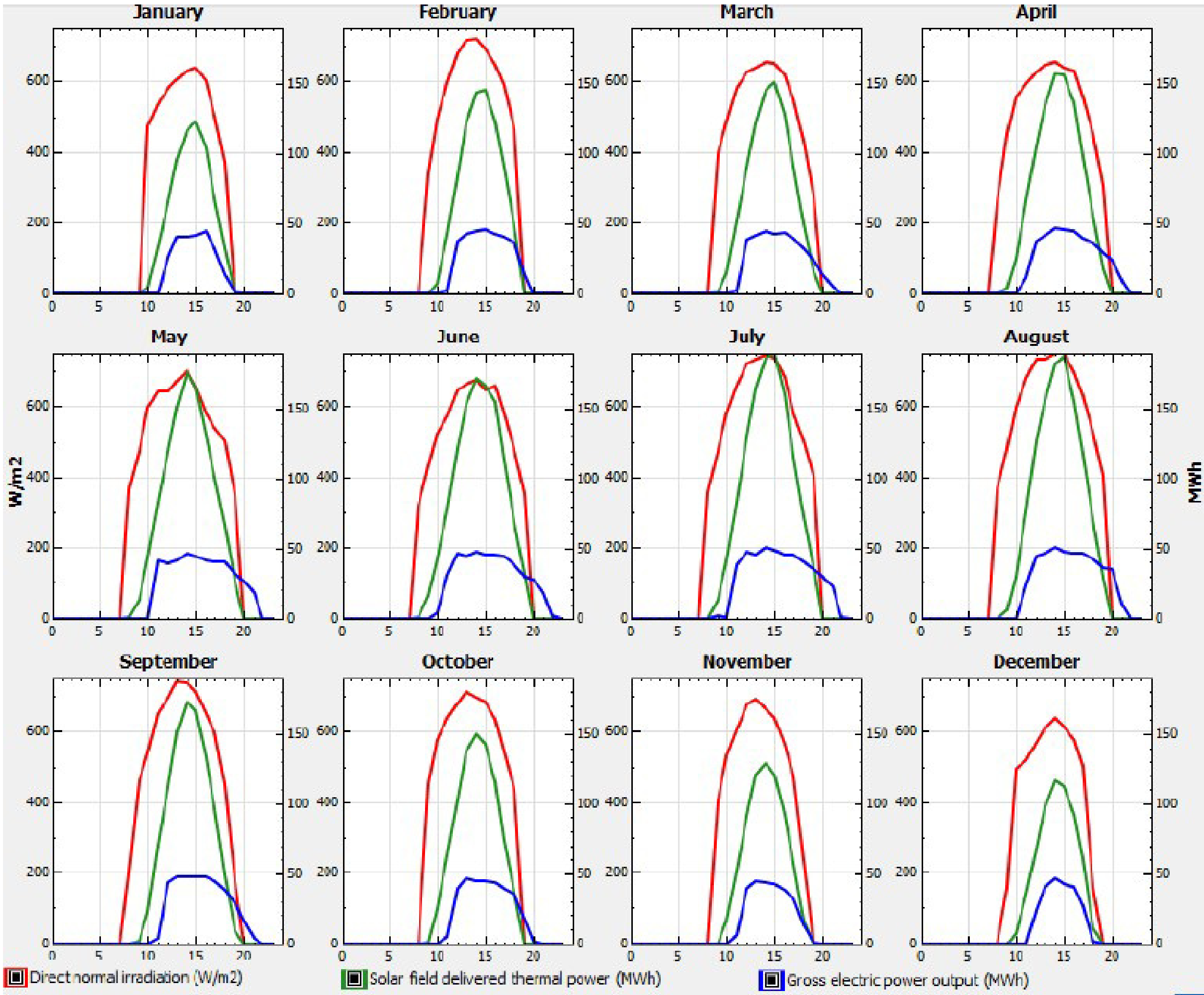

Fig. 5 – Yearly available resource, Thermal Power, Net electricity output

Table 7. Parametric analysis varying the solar multiple

Solar Multiple	Mirror Area [m^2]	Yearly Net [GWh] no storage	Yearly Net [GWh] storage 7h
2,0	420.000	92	110
2,5	525.000	107	147
3,0	630.000	115	172

It should be noticed that in Fig.4, on some sunny days, the value for the energy storage sent to the tanks is zero, this is because all the energy captured is being sent to the turbine. The need for storage only applies when the power captured is higher that the turbine nominal power.

For the base case analyzed the output is a yearly net electricity production of 110 GWh for the mirror area considered (420.000m^2) and with 7h of storage. In order to understand the solar multiple and the storage effect impact on the net electricity production, a parametric analysis is presented in Table 7. The yearly energy production increases therefore from 110GWh to 172GWh for a solar multiple of 3,0.

3. Economic valuation

3.1. Input parameters

As explained above this paper seeks no economic optimization and calculates what is expected from a configuration for which storage is of 7 hours and the solar multiple is 2, given that this configuration is already capable of demonstrating the low cost potential of the configuration/solution proposed.

In order to evaluate the economical value of an investment made for electricity production, the Levelized cost of electricity (LCOE, Eq.4) considering the actualized Cash Flows for the total economic lifetime of the project was calculated.

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (4)$$

CAPEX and OPEX were taken into consideration divided into two cases. Case 1, considers a Solar Field (SF) cost of 150 Euro/m^2 which is a reference value for plants recently built in Spain [6,10]. Case 2, takes into consideration the possibility that the SF cost might go down to 100 Euro/m2. Due to the significant reduction of the piping, lower pressure drop in the circuit, the Balance of Plant (BOP) costs considers 25% savings when comparing with similar size PTC plants. The costs considered for the Power Block (PB), Storage (ST), HTF, Engineering/Procurement/Construction (EPC) are costs in line with the available literature [7,8,9,10], which in turn have a well identified cost reduction potential. The fuel costs are zero, which is one of the great advantages of renewable energy investments, since there is no associated uncertainty or fear of future high fuel costs. The economic lifetime considered was 25 years, however, with the experience of the SEGS plants built in the USA in the early 80's, one can assume that plants currently being built, their lifetime can easily be extended for another 10 years without any major investment.

Different companies have different experience levels on CSP, and also different views on the risk level they are willing to assume. Therefore, a sensitivity analysis was performed varying the discount rate (11 to 13%). For an industrial investment in technologies which are not in broad usage, 10% is considered to be a minimum acceptable value. This value incorporates the interest paid for the capital borrowed, the capital premium (on top of risk free investments), and also a remuneration decided by the Company Board. Companies with a long track record, with related experience in building and operating CSP plants will tend to tolerate a lower discount rate, since they know well the business. Other companies, which might be new in this field, they would apply a higher discount rate.

Table 8. Economic input data used for Levelized cost of energy (LCOE) calculation

Variable	Value
CAPEX-1 (case 1: SF 150Euro/m^2)	SF 63, PB 40, ST+HTF 50, BOP 24, EPC & others 18 = 195 MEuro
CAPEX-2 (case 2: SF 100Euro/m^2)	SF 42, PB 40, ST+HTF 50, BOP 24, EPC & others 18 = 174 MEuro
Economic Lifetime	25 years
OPEX annual costs	3,0 MEuro/year
Fuel costs	0 Euro
Equity / Debt Ratio	50%

Table 9. LCOE calculation [cEuro/kWh.year], sensitivity analysis for different doscount rates

Discount Rate	Case 1: SF cost of 150E/m2	Case 2: SF cost of 100E/m2
r= 13%	12,6	11,4
r= 12%	12,3	11,1
r= 11%	12,0	10,8

3.2. Discussion of results

The results presented show that the new LFR SMS XX, for companies already with experience in CSP, can achieve LCOEs approaching 10 euro cents/kWh with 7 hours of storage. In particular 10,8 cEuro/kWh.year for the minimum discount rate considered of 11%, in a location like Faro. Although a very sunny European spot, it is still far from sunnier places in excess of 2600kWh/m2.year or locations with lower latitudes, where lower LCOE values can be obtained, with the same assumptions made above.

Further potential lower values can be obtained from performance increases (this can come through optimization of the proposed optics, still not yet at the limit of what is possible to achieve, in particular through further EM conservation to be done in future work). Besides, increasing the Solar Multiple to 3 which is a common value in order to take full advantage of the relative investment cost in storage facilities, it would lead to a further reduction of 1,7 cEuro, that is a LCOE of 9,1 cEuro/kWh.year. This figure indicates that if an optimization of the solar field size is performed together with other cost saving measures (e.g. one tank system) values below 10cEuro/kWh.year are possible even for a sunny European location with this new concentrator and associated technology.

4. Conclusions

The objective of this paper is to show that there is an enormous potential, yet to be explored, in linear focus technology, namely in low cost LFR technology and encourage other researchers and companies to pursue it.

In this study, a new Fresnel concept called SMS XX has been presented, showing that there is a good theoretical potential for optical improvement (C=74x) of the Fresnel collectors currently in use for CSP. For a sunny European location (Faro - Portugal) the total energy produced is 110 GWh with 7h storage, considering a solar multiple of 2,0.

This could, in principle, be achieved with an LCOE of 10,8 cEuro/kWh.year. This value can still be reduced, with a further optimization of the optics itself and jointly with the rest of the solar field, power block and storage size.

This paper aims at showing that the combination of high performance new LFR concentrators with molten salts as HTF and storage fluid, can lead to a truly interesting low cost for electricity production. However it is clear that several aspects of the concept, from the new concentrators to many yet untried operational issues, must be practically investigated and implemented, to establish their true worth.

At present, significant R&D is being proposed to the H2020 program, for the research and development of the new LFR concept achieving the referred high concentration for an efficient coupling with molten salts as HTF fluid.

Concerning the salts it is crucial to test them for the first time jointly with this new Linear Fresnel concept, extending the research also to new operational and control technologies for the concept as a whole. In particular Linear Fresnel concentrators with their fixed receivers, are naturally suited for the consideration of drain down techniques, eliminating some of the most serious draw backs of using molten salts as HTFs, something that should indeed be developed.

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References

[1] Canavarro, D. et al, "Simultaneous Multiple Surface method for Linear Fresnel concentrators with tubular receiver", Solar Energy 110 (2014) 105-116
[2] CSP current Projects Database, accessed on 30/06/2014, www.nrel.gov/csp/solarpaces
[3] Mills, D.R.; Morrison, Graham L. "Compact linear Fresnel reflector solar thermal power plants". Solar Energy.68 (2000): 263–283
[4] Chaves, J., Collares-Pereira, M., "Etendue-matched two-stage concentrators with multiple receivers", Solar Energy 84 (2010):196-207
[5] Peng, Q. "Design of new molten salt thermal energy storage material for solar thermal power plant", Applied Energy, 112 (2013)
[6] Morin, G. et al."Comparison of Linear Fresnel and Parabolic Trough Collector power plants", Solar Energy 86 (2012): 1-12
[7] NREL Report nº SR-550-34440, "Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts" (2003)
[8] Charles, R. "Assessment of Concentrating Solar Power Technology cost and performance forecasts", Electric Power 2005
[9] Hoyer, M. et al., "Performance and Cost Comparison of Linear Fresnel and Parabolic Trough Collectors", 15th International SolarPACES Symposium, Sept. 14-18 2009, Berlin, Germany
[10] Morin, G. et al., "Comparison of Linear Fresnel and Parabolic Trough Collector Systems – Influence of Linear Fresnel Collector Design Variations on Breakeven Cost", 15th International SolarPACES Symposium, Sept. 14-18, 2009, Berlin, Germany
[11] Novatec Solar, NOVA-1"Turnkey solar boiler, mass produced in industrial precision – with performance guarantee", NOVA-1 brochure.
[12] Guerreiro, L., Collares-Pereira,M. "Energy output and thermal losses in a PTC molten salts test loop", Proceedings of Solar Paces 2014
[13] Chaves, J., 2008, „Introduction to Nonimaging Optics", CRC Press, Taylor and Francis Group.
[14] Miñano, J.C., et al., „High efficiency nonimaging optics", United States Patent 6.639.733, 2003.